First Observations at PHENIX of W Production from Polarized pp Collisions at RHIC

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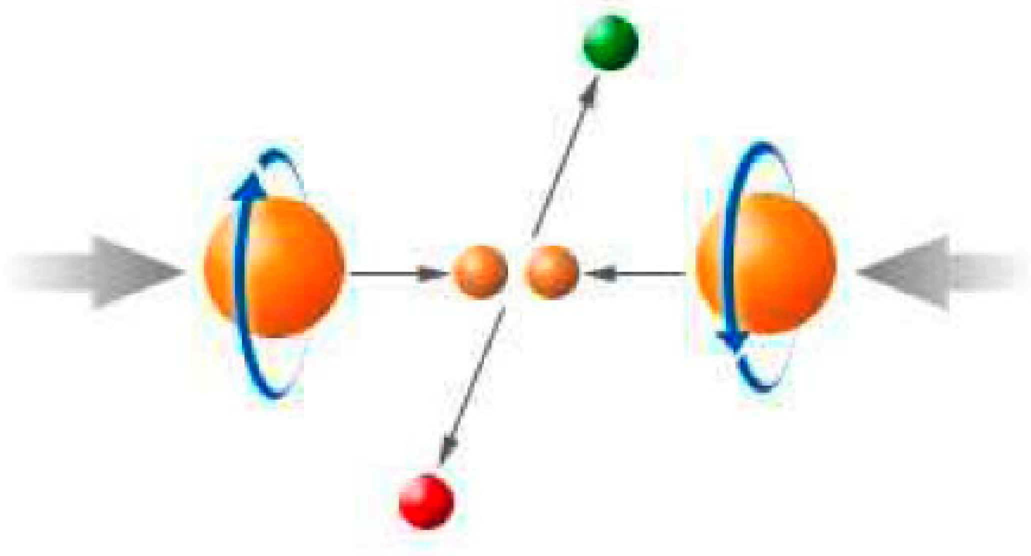
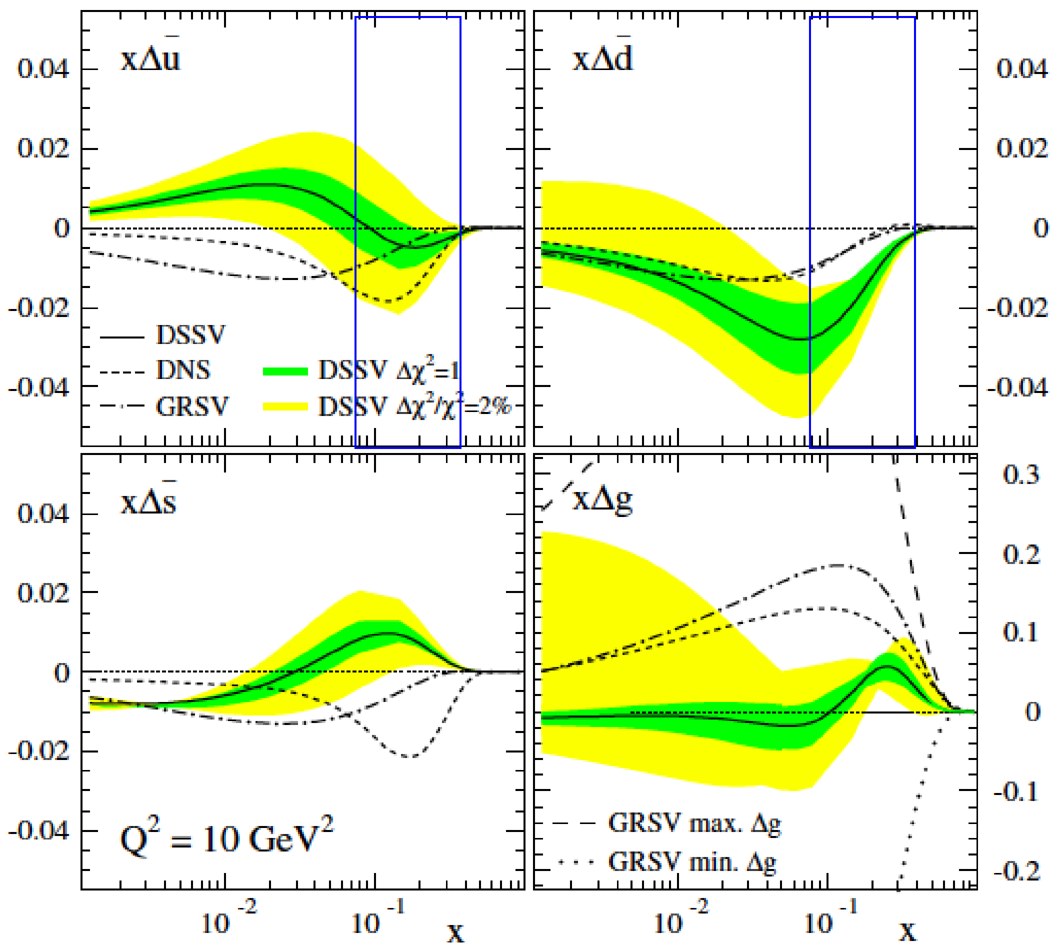
on behalf of the PHENIX Collaboration



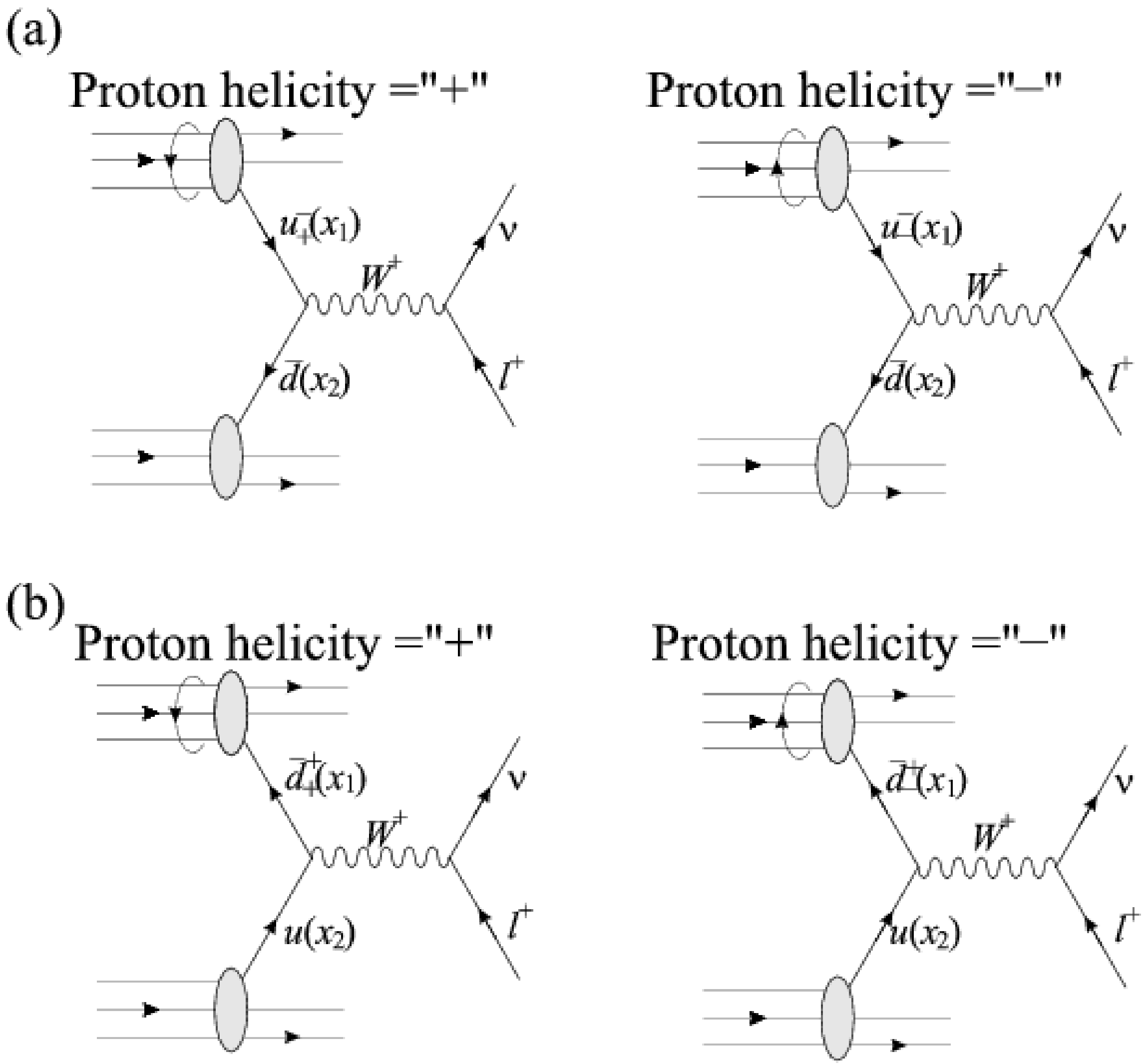
Motivation for Spin Physics with Ws at RHIC

- Key measurement of spin program : flavor separated, polarized PDFs $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$
- Semi-inclusive polarized DIS experiments (SMC, HERMES, COMPASS) have made such measurements
- STAR and PHENIX can do it exploiting maximal-parity violation in W production in polarized pp collisions
  - Measurements made at high scale ($M_W^2 > 6000$ GeV^2)
  - No uncertainty from fragmentation (couplings of W well known), no higher twist effects



- Unpol. PDFs known to about 10%
- Theoretical uncertainties small (NLO+resummation)
- Robust extraction of $\Delta\bar{u}(x)$ and $\Delta\bar{d}(x)$
- Can also measure ratio $\bar{u}(x)/\bar{d}(x)$

$\Leftarrow$ D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, Phys. Rev. Lett. **101**, 072001 (2008)
(At $Q^2 = 10$ GeV^2)



- Sensitivity to polarized PDFs by taking difference in W production rates when incoming proton helicity changes sign

(a) u always left-handed : Δu probed in polarized proton

(b) $\bar{d}$ always right-handed : $\Delta \bar{d}$ probed in polarized proton

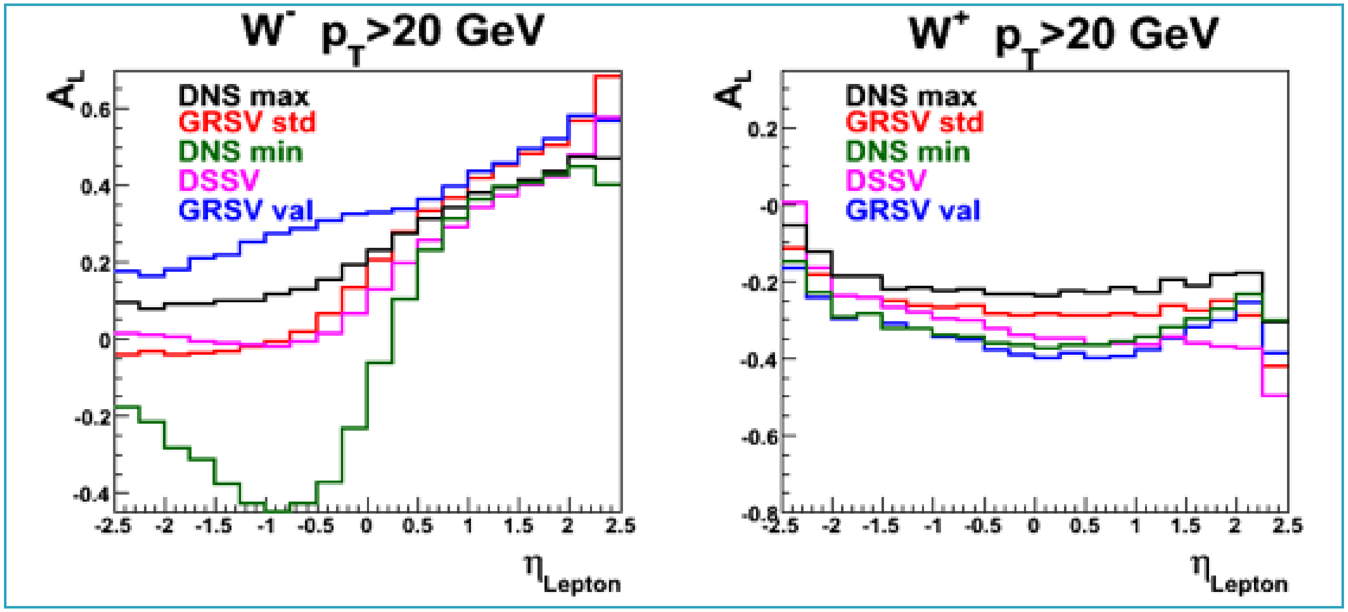
- For W^-, $\Delta \bar{u}(x)$ and $\Delta d(x)$ probed

  (From Bunce *et al.* Annu. Rev. Nucl. Part. Sci. **50** 525 (2000)).

Central arm measurement $pp \to W \to e$ probes PDFs at :

$$\langle x_{1,2} \rangle \;\approx\; \frac{M_w}{\sqrt{s}} \;\exp\left(\pm y_W\right) \;\approx\; 0.16$$

Motivation for Spin Physics with Ws at RHIC



(From RHIC Spin Plan 2008)

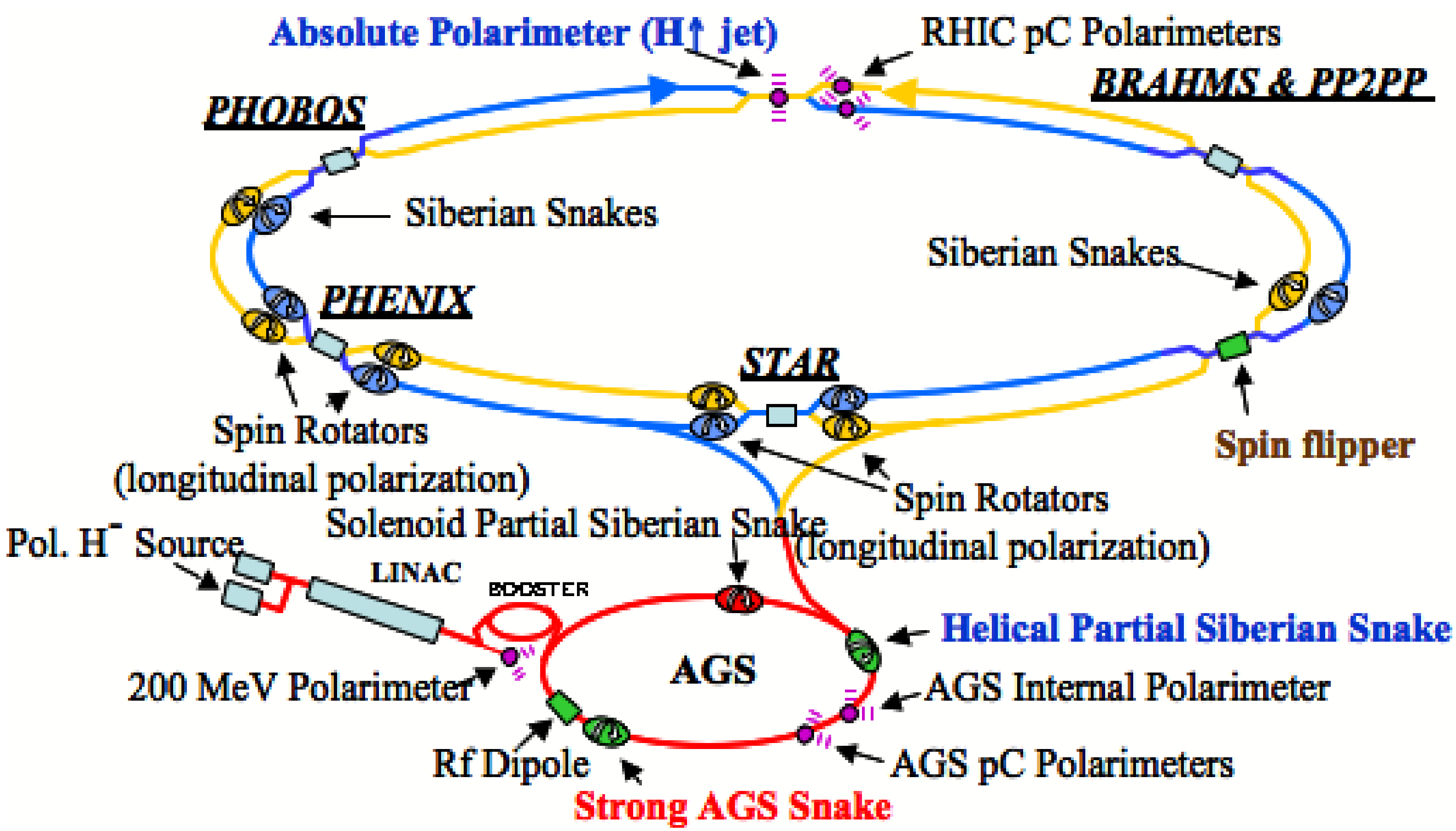
- $W^- \;:\; : A_L \;\propto\; \Delta\bar{u}(x_1)d(x_2)(1-\cos\hat{\theta})^2 - \Delta d(x_1)\bar{d}(x_2)(1+\cos\hat{\theta})^2$
- $W^+ \;:\; : A_L \;\propto\; \Delta\bar{d}(x_1)u(x_2)(1+\cos\hat{\theta})^2 - \Delta u(x_1)\bar{d}(x_2)(1-\cos\hat{\theta})^2$
- For W^+, $-0.35 < \eta_e < 0.35$, measure combination of $\Delta\bar{d}$ and Δu
- For W^-, $-0.35 < \eta_e < 0.35$, measure combination of $\Delta\bar{u}$ and Δd
- y_W can not be determined unambiguously from y_e^{lab} at mid-rapidity :

$$y_e^{lab} = \hat{y}_e + y_W \;,\; \text{where } \hat{y}_e = \frac{1}{2}\ln\left[\frac{1+\cos\hat{\theta}}{1-\cos\hat{\theta}}\right] \;,\; p_T^e \approx \frac{M_W}{2}\sin\hat{\theta} = \frac{M_W}{2}\sin(\pi-\hat{\theta})$$

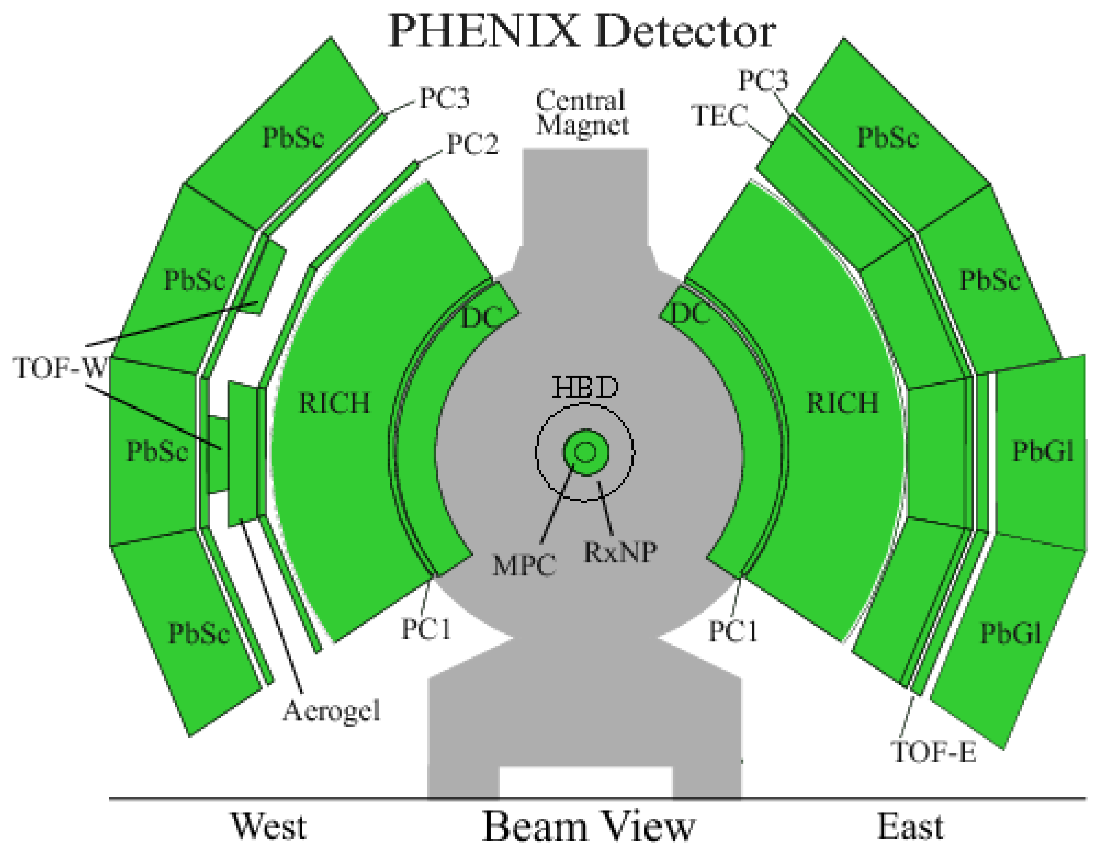
- Irreducible uncertainty in sign, $P_T^W \neq 0$ either, extraction of $\Delta\bar{u}(x),\ \Delta\bar{d}(x)$ not trivial

RHIC : World's Only Polarized Proton Collider

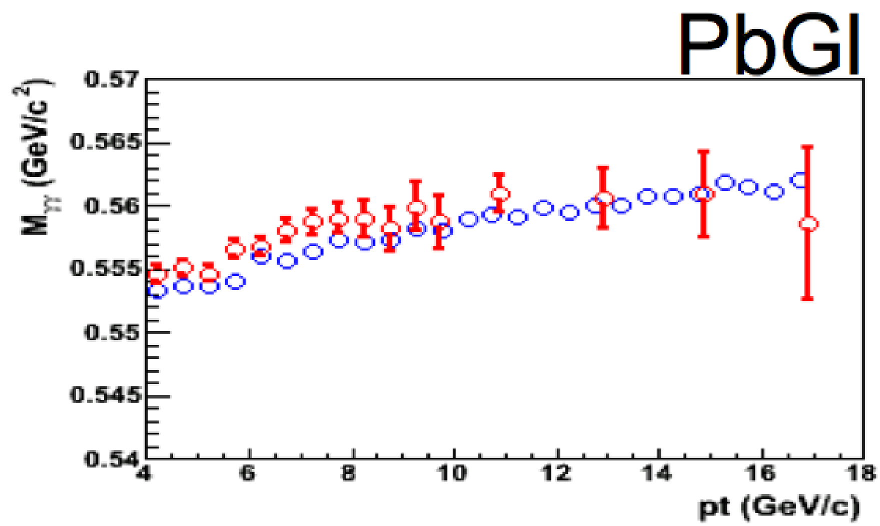
- Run 09 : Longitudinally polarized pp at $\sqrt{s} = 500$ GeV/c (Mar.17-Apr.13, 2009)
- Peak Luminosity in 2009 : $\mathcal{L} = 6 \times 10^{31}$ cm^{-1}s^{-1} ($\mathcal{L}_{\text{Design}} = 2 \times 10^{32}$ cm^{-2}s^{-1})
- Average Polarization : $\langle P \rangle = 0.39 \pm 0.04$ (measured with C CNI polarimeter, calibrated with H jet)
- Integrated Luminosity for this analysis : $\int \mathcal{L} dt \approx 17.2$ pb^{-1}



- Up to 120 bunches in each ring, crossing every 106 ns, helicity of pairs $++, +-, -+, --$ alternates rapidly



- Electromagnetic calorimeter (EMCal) finely segmented : $\Delta\phi \times \Delta\eta \approx 0.01 \times 0.01$
- Calibrated with $M_{\gamma\gamma}$ of π^0 at high p_T

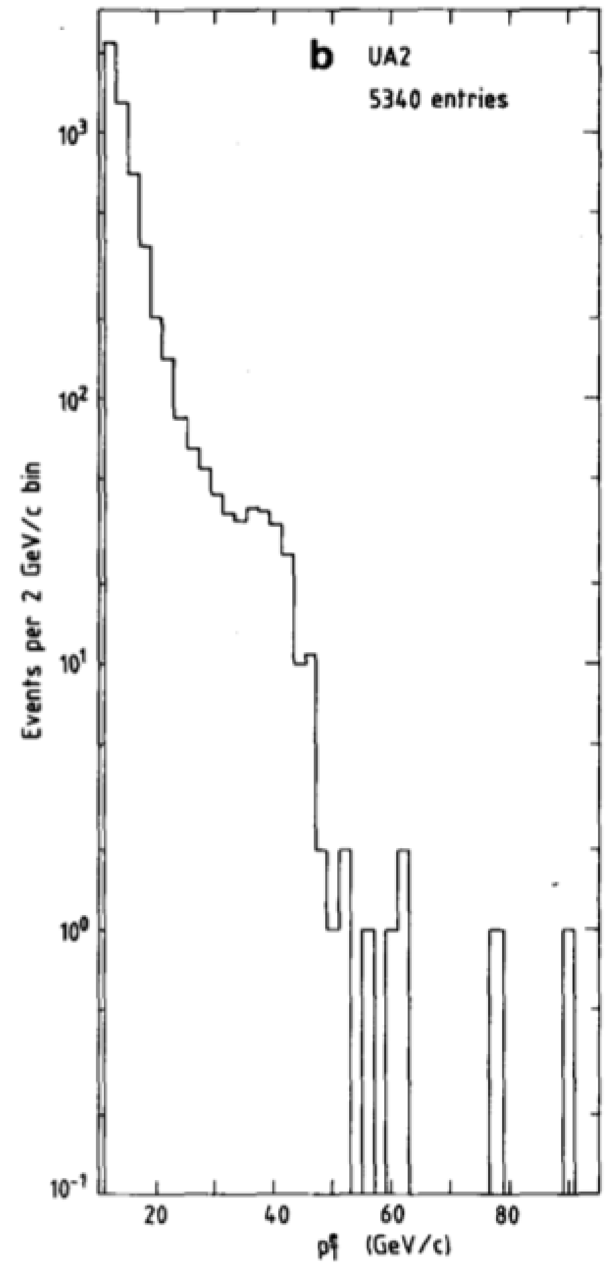


$\Rightarrow$ Focus on $\vec{p}p \Rightarrow W^{\pm} + X \Rightarrow e^{\pm} + X'$

- Detect high E $e^{\pm}$ in central arms of PHENIX
- Acceptance of each arm : rapidity $|\eta| < 0.35$ $(70 < \theta < 110)$, $\Delta\phi = \pi/2$
- Vertex cut : $|z| < 30$ cm

- Tracking : Charged tracks measured in Drift Chamber (DC) and Pad Chamber(PC1)
- $\int \vec{B} \cdot d\vec{l} = 0.78$ Tesla-meters

- Can't identify $W \Rightarrow e + \nu_e$ definitively on event-by-event basis
- Like UA1 and UA2 : looking for excess of events above background :
  (R. Ansari *et al.* (UA2 Collaboration), Phys. Lett. B**186**, 440 (1987))

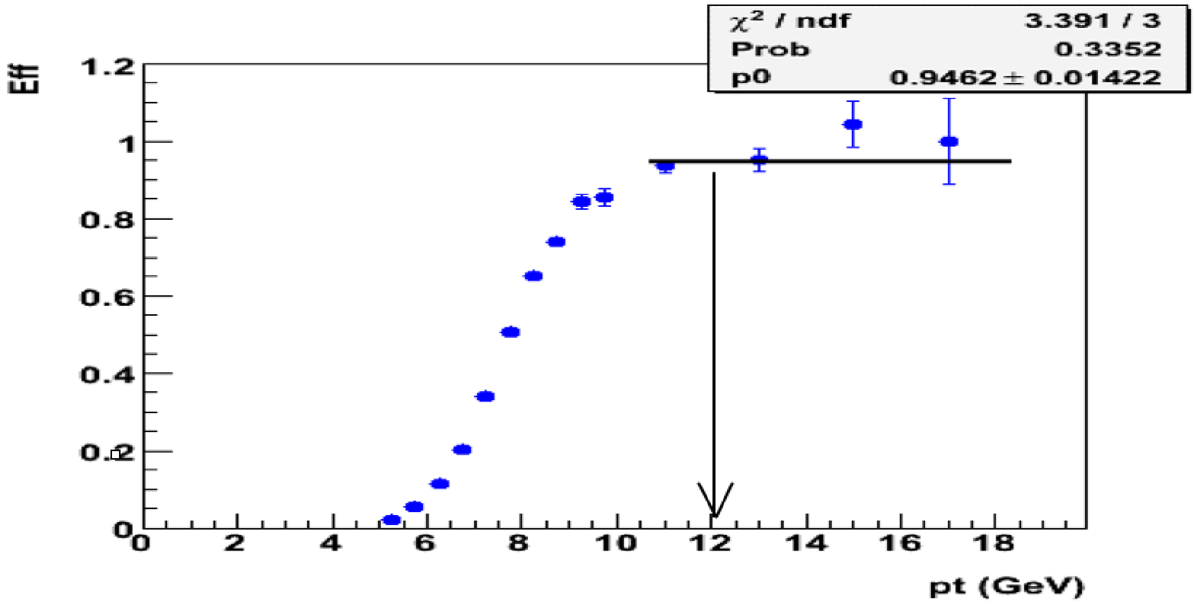


Find the Ws

Backgrounds : Reducible and Irreducible

- Can't identify $W \Rightarrow e + \nu_e$ definitively on event-by-event basis : rely on excess of events over background
- Reducible Backgrounds : Collision-independent
  - Cosmic rays
  - Beam related backgrounds (fragments, halo, scattering upstream)
  - Timing cuts reduce by more than factor of 5
- Backgrounds : Collision-dependent
  - $\pi^0,\ \eta \Rightarrow \gamma\gamma$, or direct-$\gamma$: conversion $\gamma \rightarrow e^+e^-$ yields cluster + matching track
  - $h^\pm$+hadronic shower in EMCal : cluster + matching track
  - π^0 or direct-γ with accidentally matching track from other fragments
- Irreducible Backgrounds
  - Irreducible in the sense they pass our cuts (high energy cluster+matching track)
  - Charm, bottom $\Rightarrow e^\pm$+anything
  - Other W decays : $W \Rightarrow \tau + \nu_\tau \Rightarrow e\nu_e\nu_\tau\bar{\nu}_\tau$, detect e
  - $Z/\gamma^* \Rightarrow e^+ + e^-$, detect one e, other outside acceptance
  - $Z \Rightarrow e^+ + e^-$ rate significant compared to $W^- \Rightarrow e^- + \bar{\nu}_e$
  - Z production comes with a small parity-violating asymmetry

- Trigger : EMCal 4x4b tower sum
  - Nominal threshold 7.5 GeV
  - Fully efficient above 12 GeV
  - No vertex requirement
- For high energy cluster in trigger module : look for matching track in DC and PC1
- Extrapolate track back : apply vertex cut $|z| \leq 30$ cm



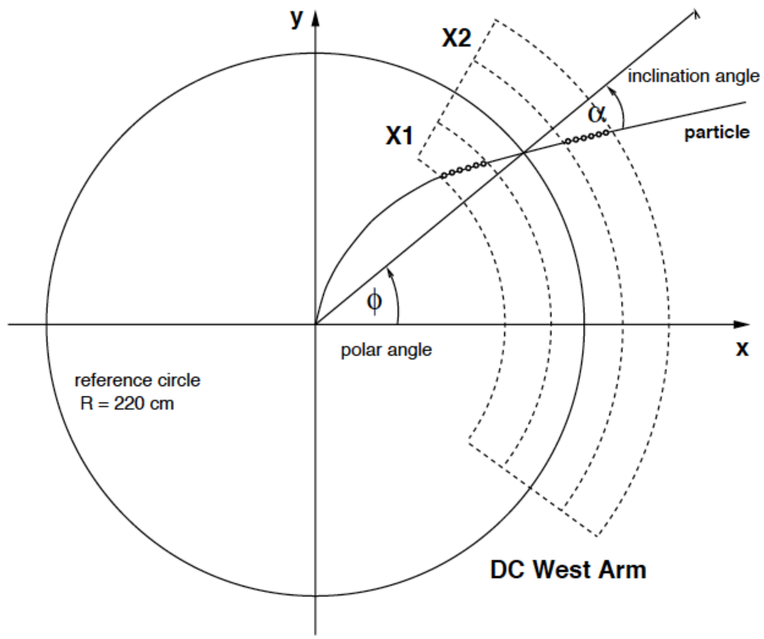
- Peak collision rate $\geq$ 2.5 MHz
- Crossing rate $\approx$ 10 MHz

⇒ Significant prob. of ≥ 1 collision/crossing

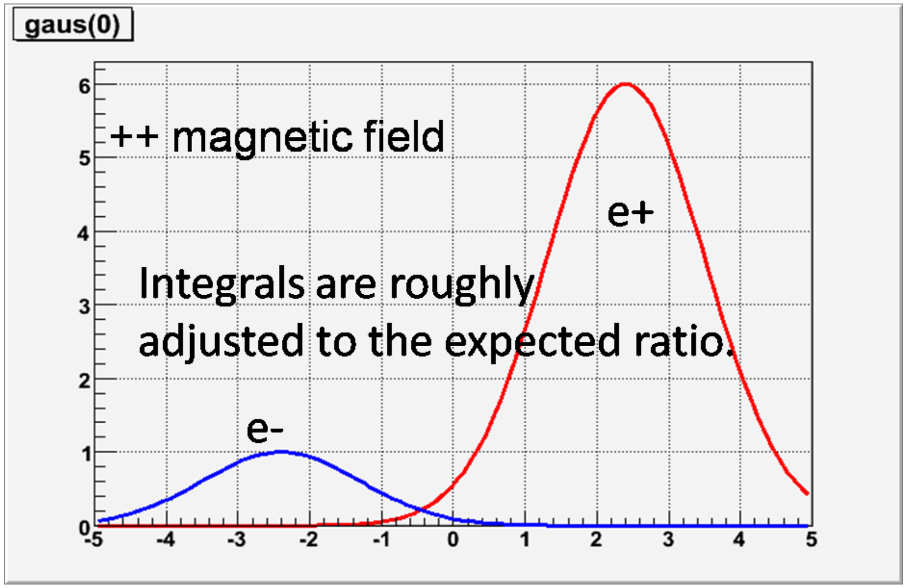
- High collision rate : Pileup in calorimeter and tracking detectors
- Timing cut based on event time in EMCal : -10 ns $< T_{\text{event}} <$ 20 ns; helps removes background from pileup and cosmics

Charge Separation : e^+ or e^- ?

- Must distinguish $W^+ \Rightarrow e^+ + \nu_e$ from $W^- \Rightarrow e^- + \bar{\nu}_e$
- Momentum and charge determined in DC



- Angle at DC wrt infinite momentum track : $\alpha \approx 100$ mrad / q×P[GeV/c]
- 40 GeV/c track $\Rightarrow \alpha \approx 2.5$ mrad, $\delta\alpha \approx 1.1$ mrad

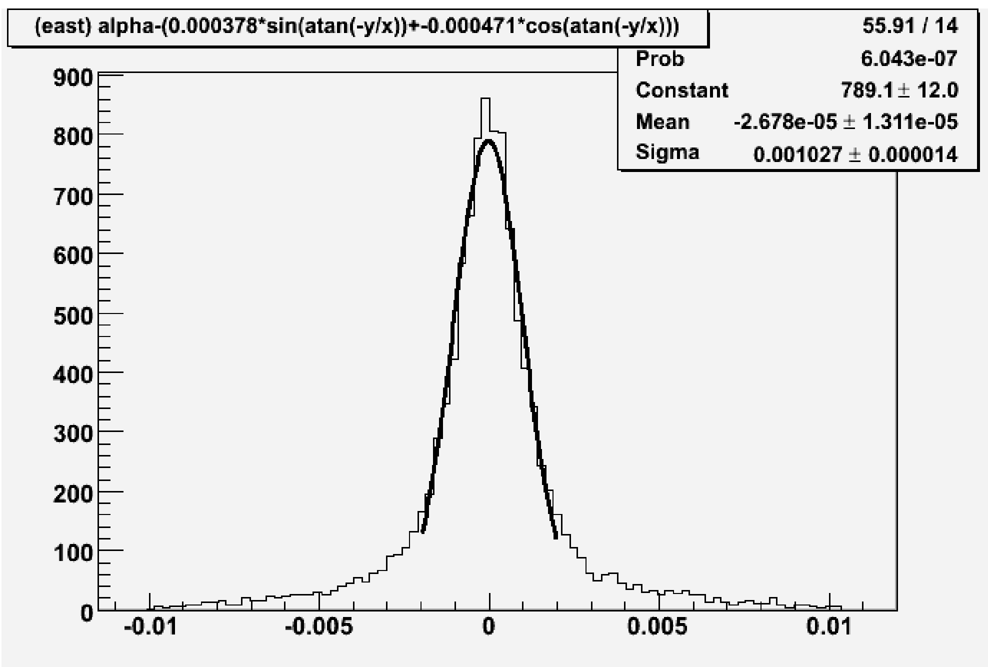


- Acceptance cuts on DC; remove tracks too close to wires to resolve L/R ambguities (15%)

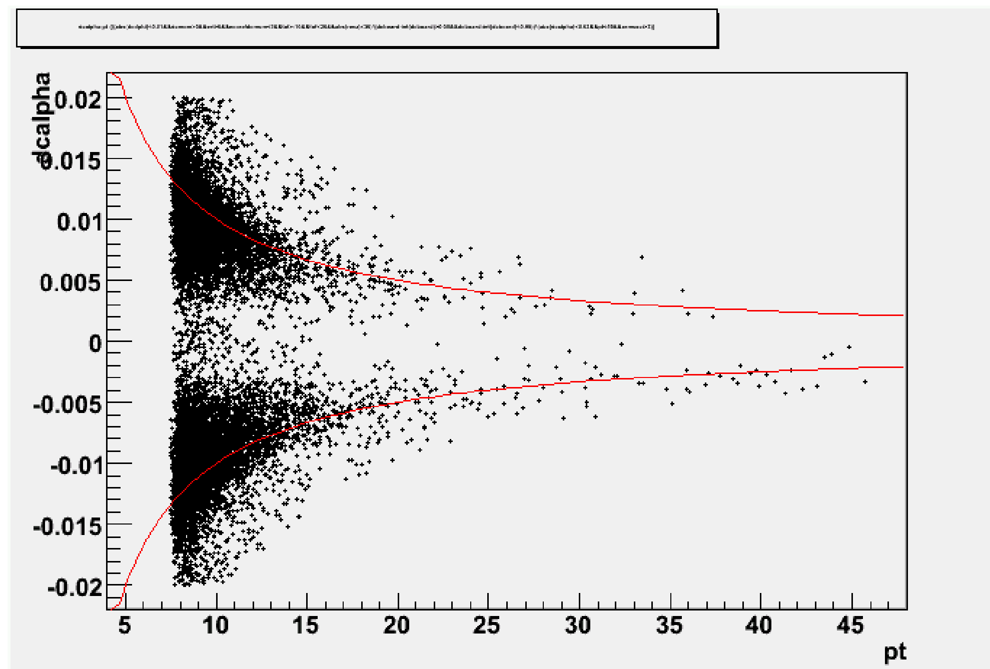
$\Rightarrow$ Charge sign determined with high confidence

- Momentum resolution $\delta\alpha/\alpha \approx \delta p/p$
- At 40 GeV/c, $\delta p \approx 40\% \times p$
- Poor momentum resolution : only loose cuts on E/p possible

- 17 zero $\vec{B}$ runs were taken : all tracks nominally have bend angle $\alpha = 0$
- Beam shifts in (x, y) affect determination of α
  - Use $\Delta\alpha$ to measure offset of beam wrt DC
- Correction to α from motion of beam center is applied (beam shifts $\pm 300\ \mu$m)
- Note that beam $\sigma_x,\ \sigma_y$ are $\approx 200\ \mu$m



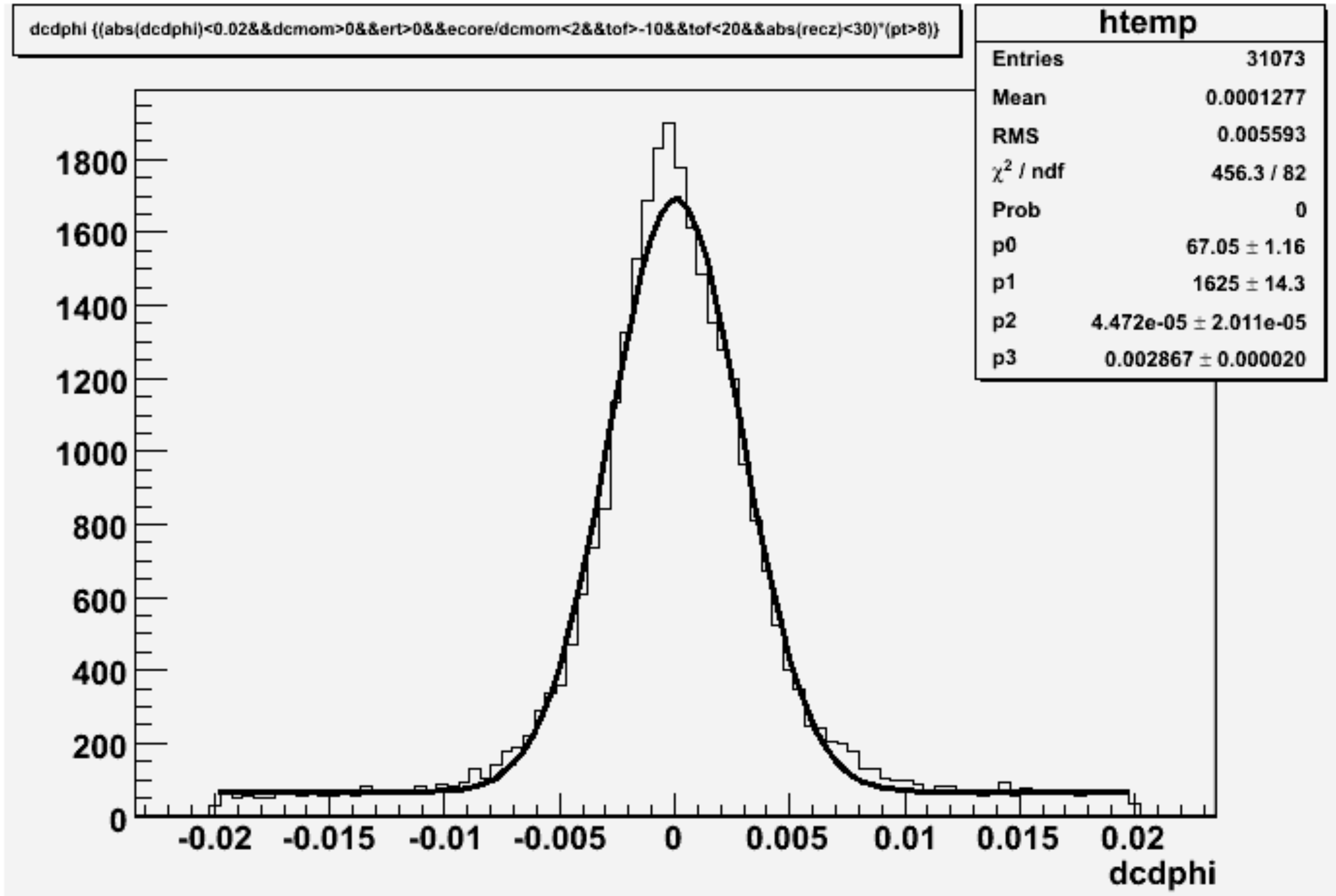
Zero-field run showing $\delta\alpha$ of tracks



Track bend angle α of DC versus p_T^{EMCal}

- $\delta\alpha \approx 1.1$ mrad $\Rightarrow$ charge separation is robust ($\lesssim 2\%$ of e^+ contamination in e^-)

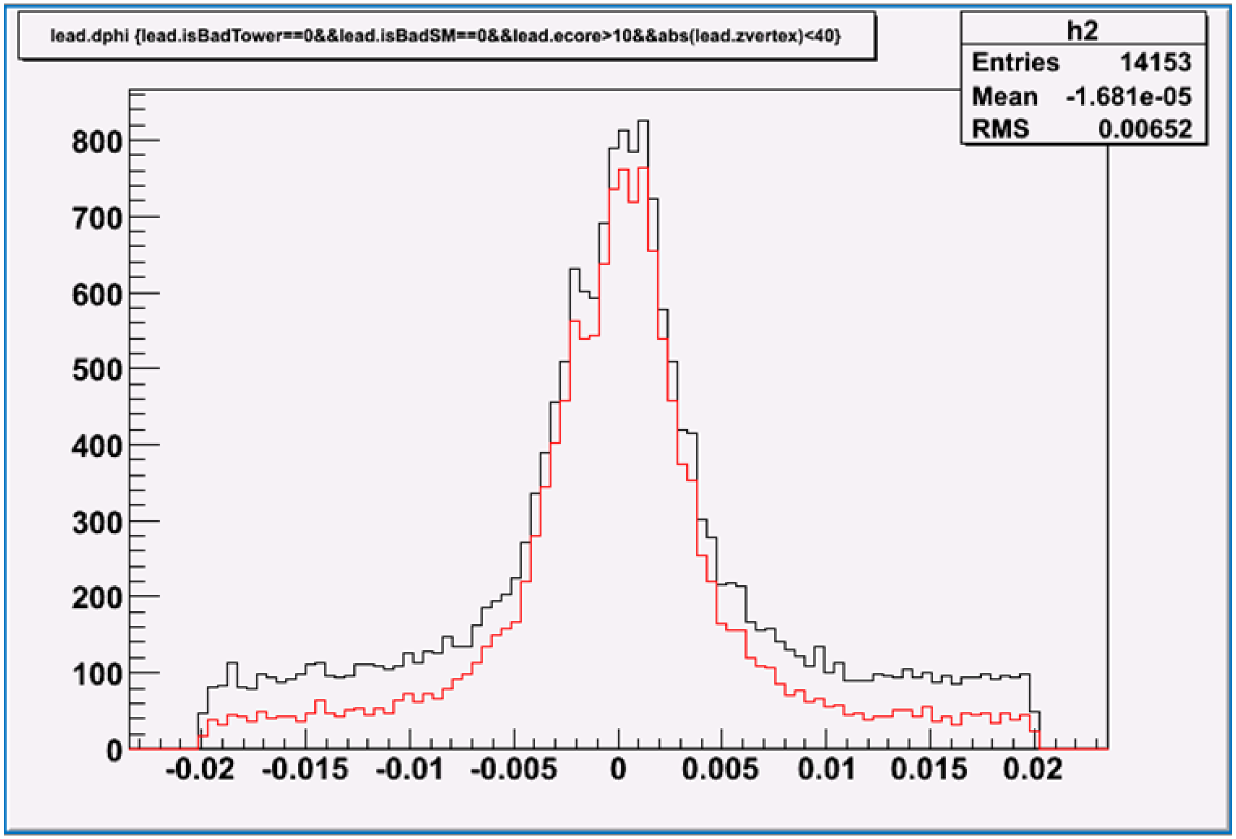
Matching of EMCal Clusters with Track



- $\Delta\phi$ between EMCal cluster and track extrapolated from DC and PC1
- Keep candidates with $|\Delta\phi| < 0.01$ radians (no match required in Δz with BBC)
- Contribution from accidental track-cluster matches extracted from tails
- Accidental match fraction consistent with PYTHIA+PISA simulation

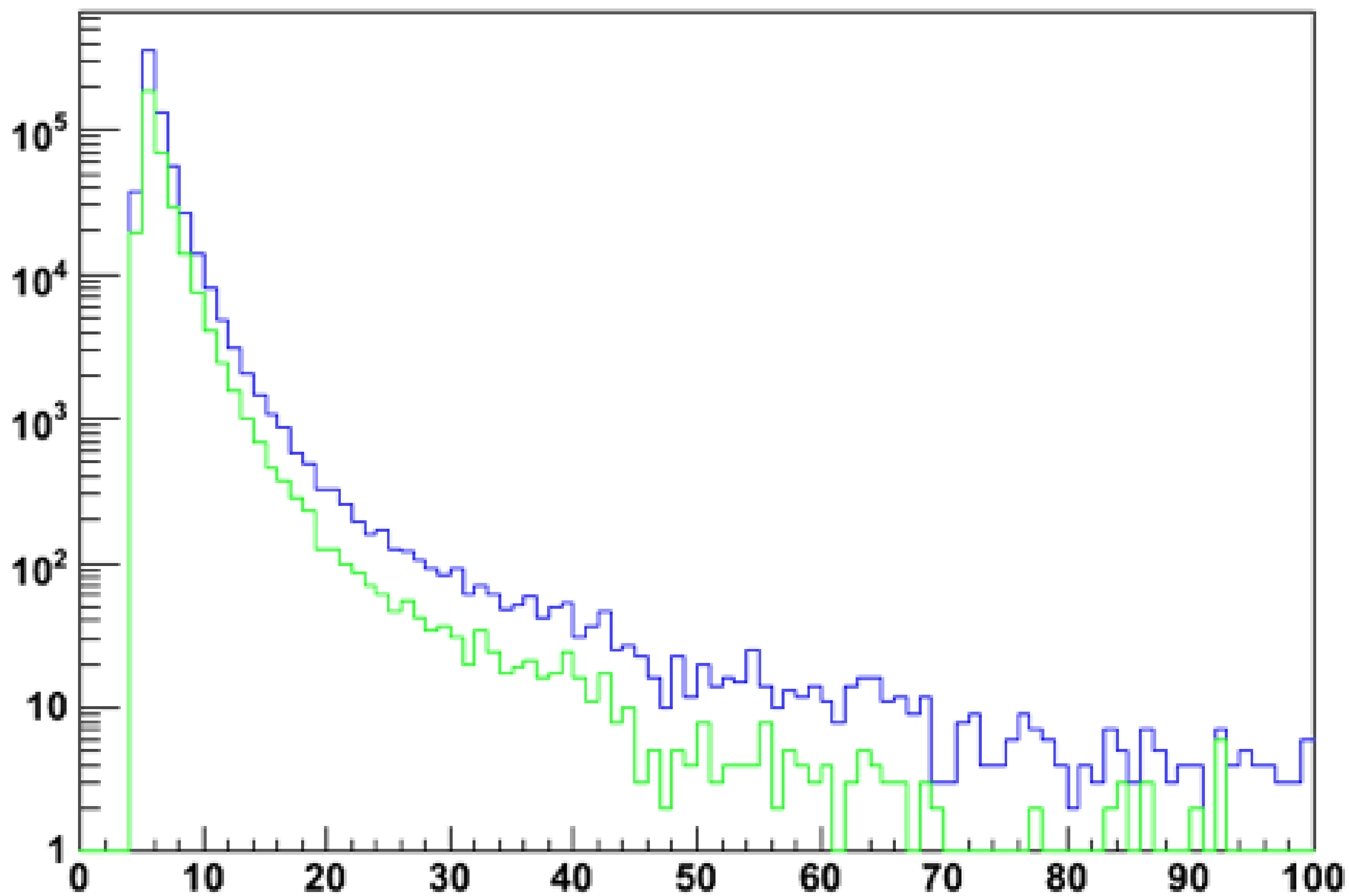
Matching of EMCal Clusters with Track with E/p cut

- Traditional e identification cuts not so useful at these high energies
  - RICH threshold of 4.7 GeV/c for $\pi^{\pm}$: requiring RICH won't eliminate high E hadrons
  - Shower shape cut normally gives $\times 2$ hadron rejection at lower energy, not easy to estimate at high E
  - Best cut left is E/p - but loose to keep signal, reflect fact that p resolution is poor



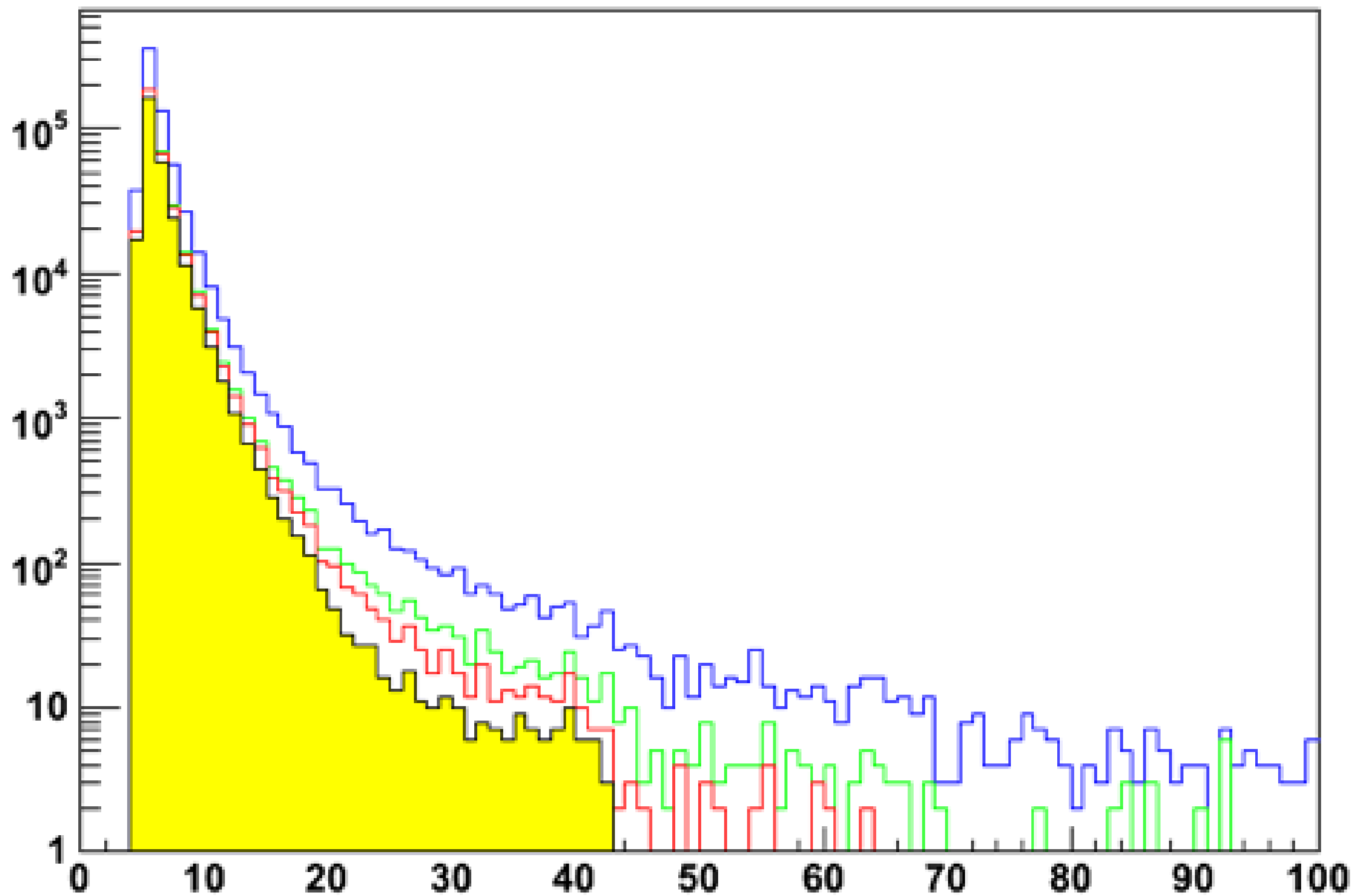
- $\Delta\phi$ [rads] between EMCal cluster and track extrapolated from DC and PC1, for cluster $>$ 10 GeV
- Black curve : without E/p cut
- Red curve : with $E/p < 3$ cut, significant reduction in accidental cluster-track matches

Analysis Results : Raw Spectrum + Matching Tracks



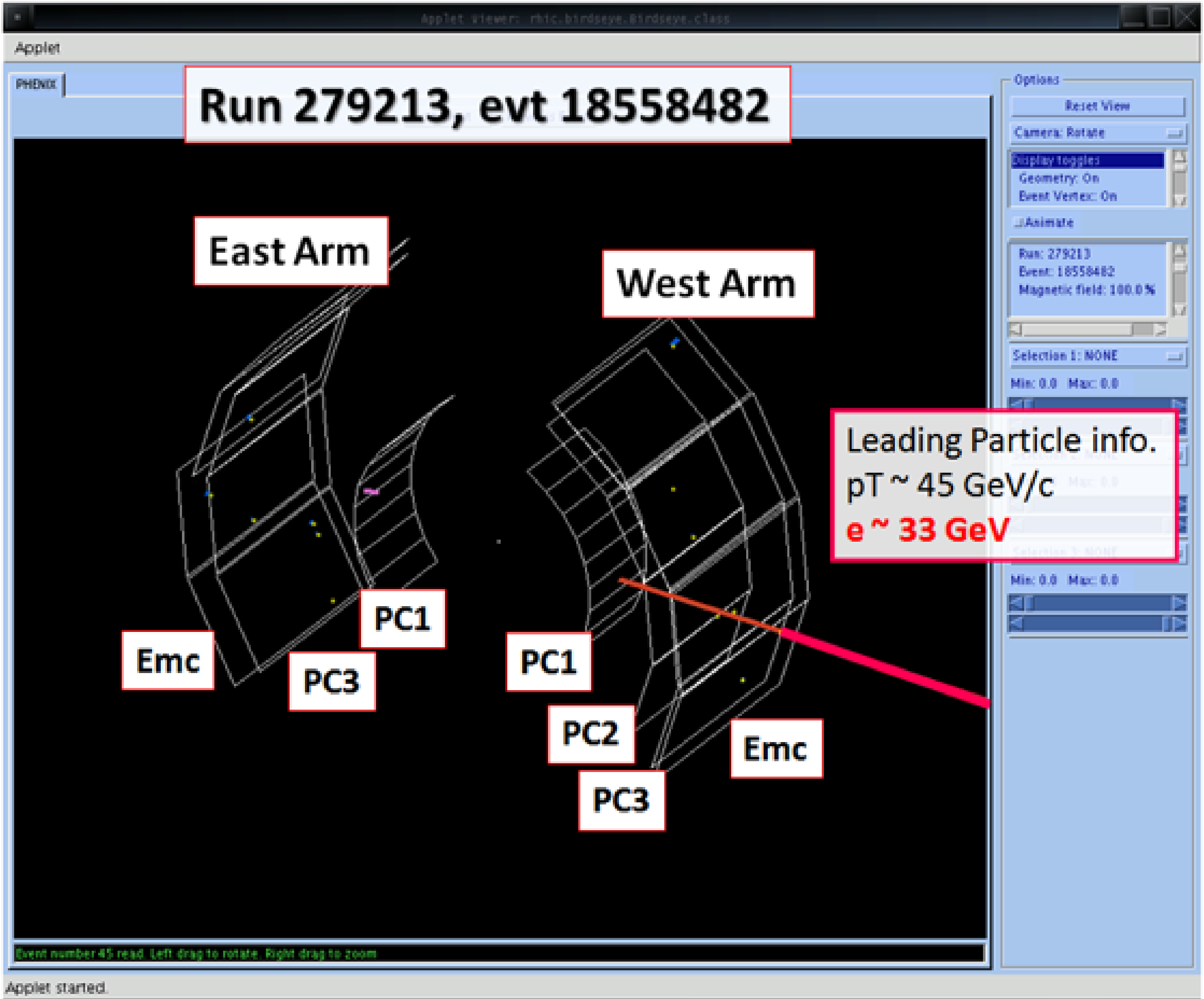
- EMCal clusters after fiducial cut, bad tower cut, versus energy
- Matching track in DC and PC1 found, $|z| \leq 30$ cm

Analysis Results : Raw Spectrum + Matching Tracks + ToF + E/p



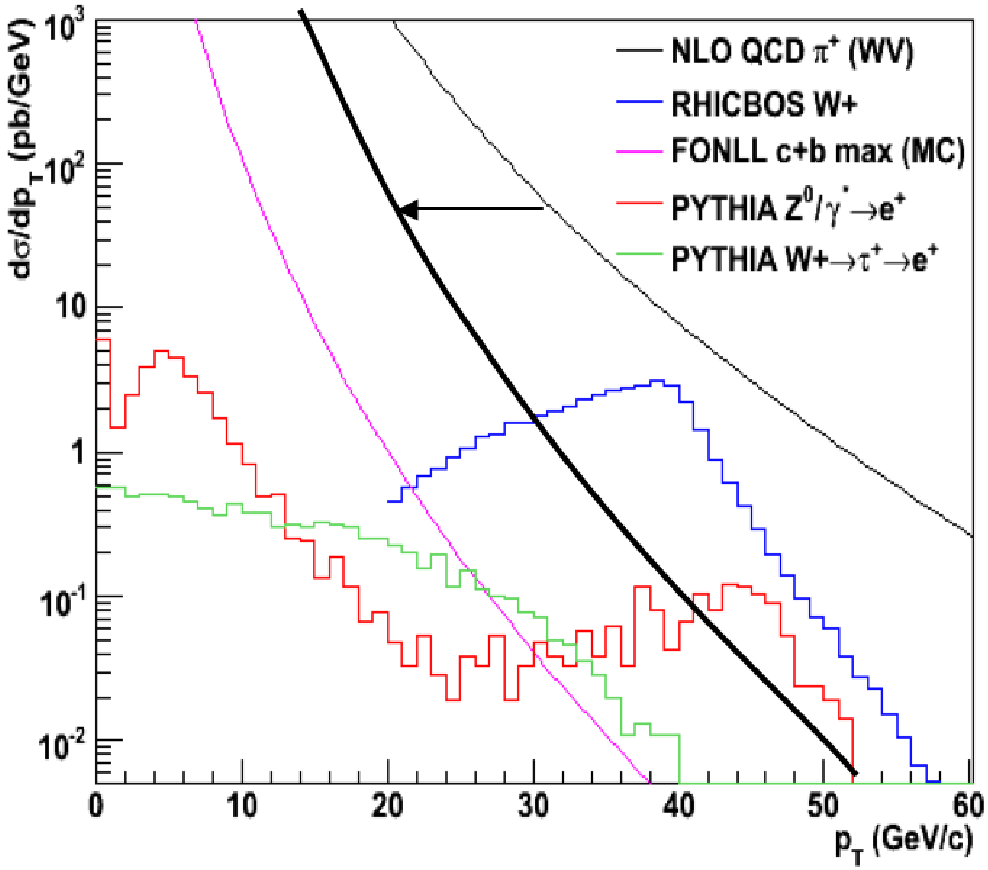
- EMCal clusters after fiducial cut, bad tower cut, versus energy
- Matching track in DC and PC1 found, $|z| \leq 30$ cm
- Cut on event time : -10 ns < $\mathrm{T}_{\mathrm{Event}}$ < 20 ns, reduces cosmics, pileup
- $E/p < 2$

W Event in PHENIX Central Arms

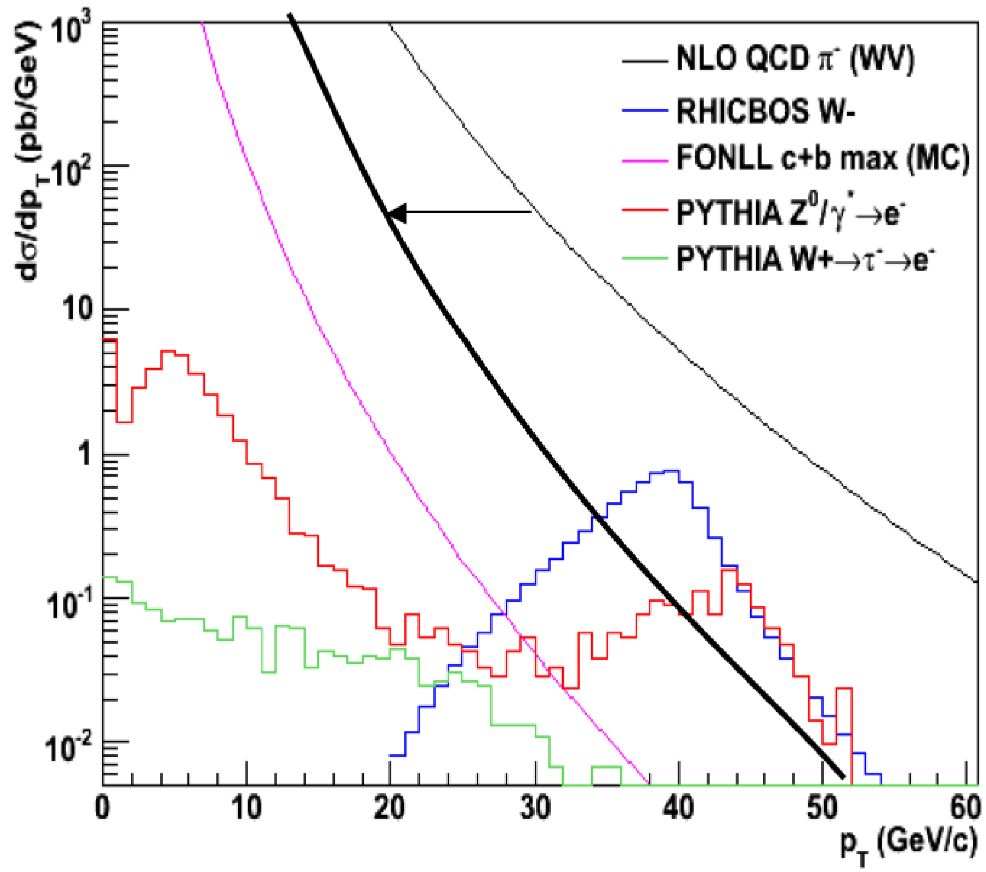


- W event in PHENIX, after many years !

Signal and Background Expectations



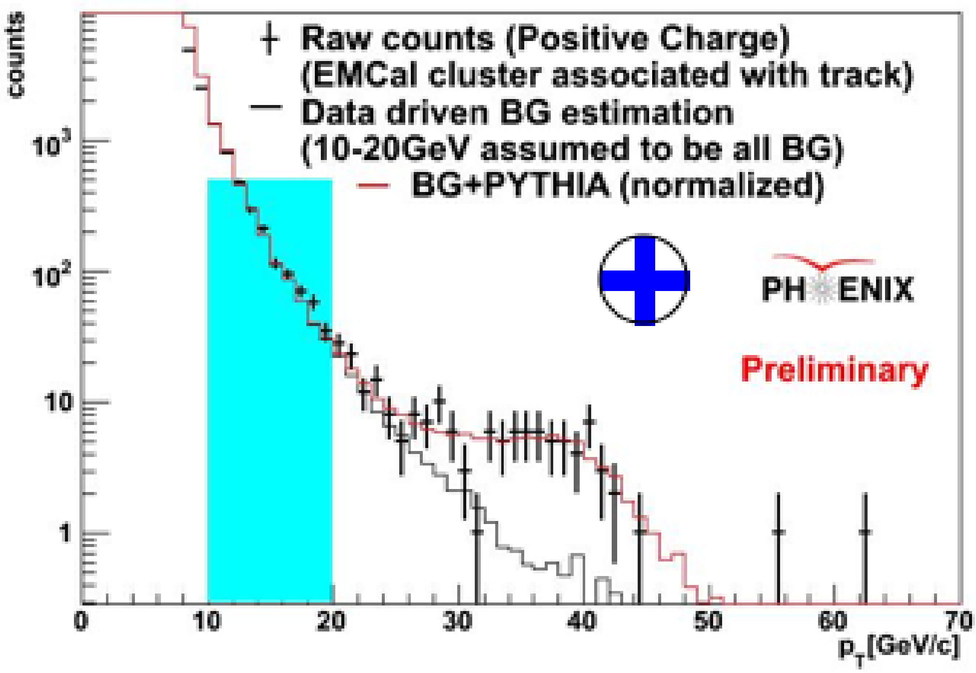
Events with Positive Charged Track

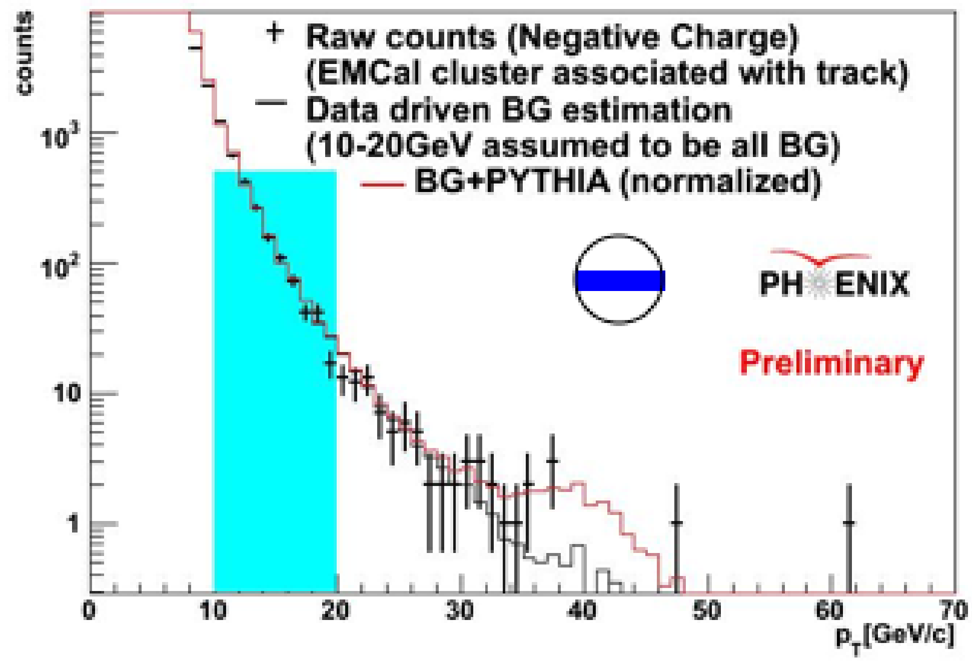


Events with Negative Charged Track

- W prediction from RHICBOS (P. Nadolsky and C.P. Yuan)
- QCD backgrounds high : rely on low photon conversion rate, low hadronic shower rate
- Charm+Bottom$\rightarrow$ e+anything relatively small
- $W \Rightarrow \tau + \nu_\tau \Rightarrow e\nu_e\nu_\tau\bar{\nu}_\tau$, high endpoint, but many body decay
- Z significant background for W^- measurement,

Comparison of Data with Background Estimation



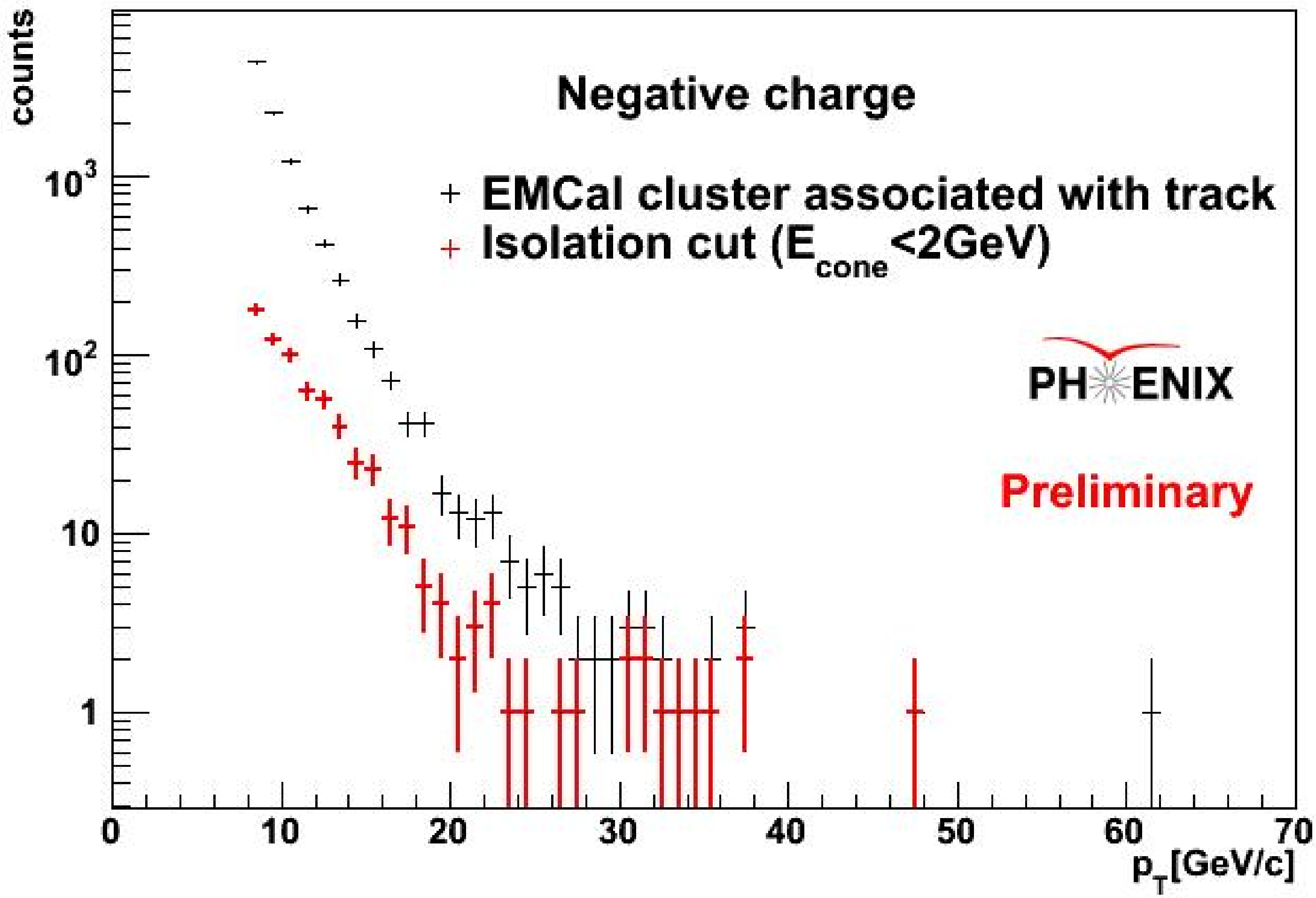


To determine background under signal region (30-50 GeV) :

- Take measured $\pi^0 + \gamma$ spectrum $\times$ conversion prob $+$ accidental matching track $\otimes$ acceptance
- Add charged hadrons (NLO) $\otimes$ detector response (GEANT) $+$ $e^{\pm}$ from FONLL c/b decays
- Normalize $h^{\pm}$ component so total background matches data in range 10-20 GeV
- Black histogram : background estimate; largest component from $\pi^0 + \gamma$, $h^{\pm}$ slightly less

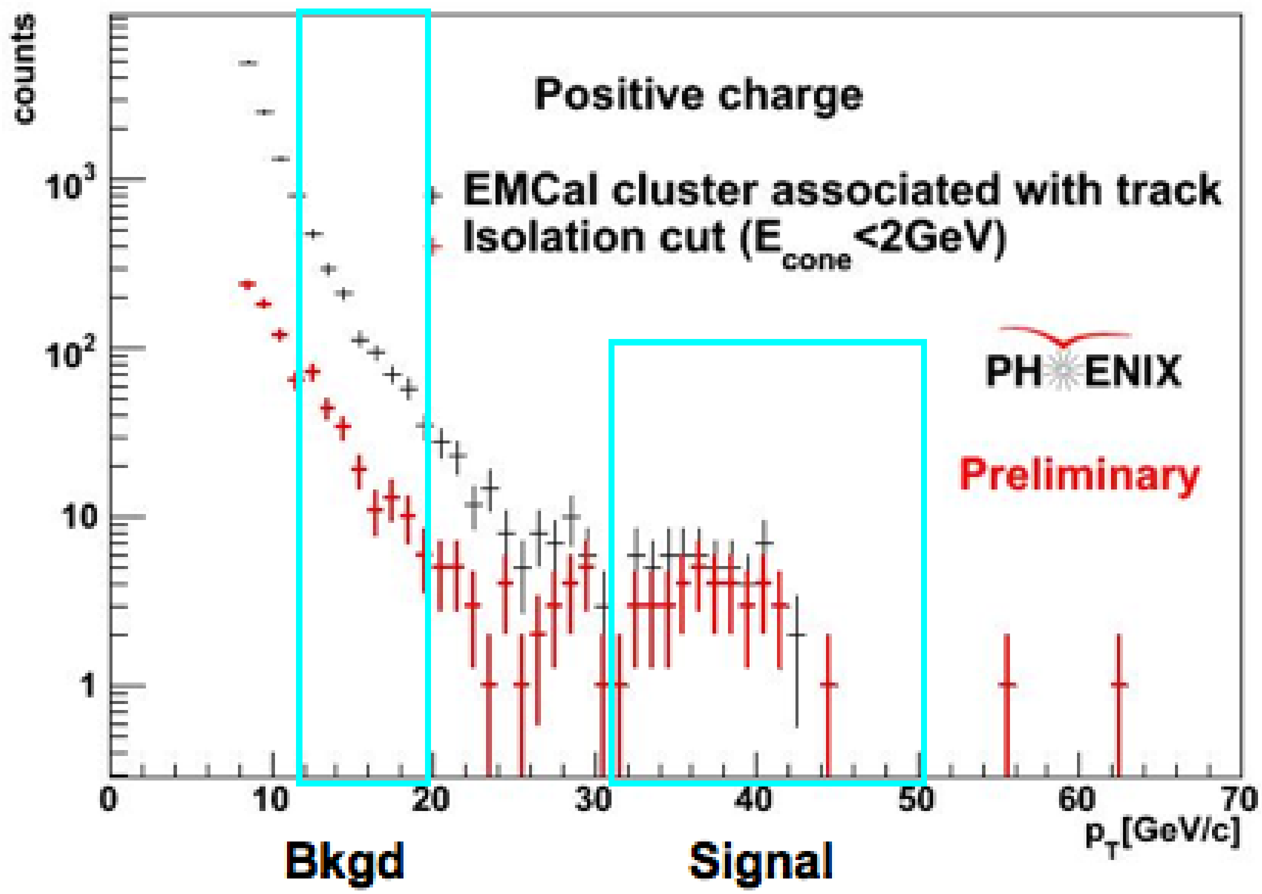
- Best measurement of A_L^W requires different cuts than best measurement of $\sigma(pp \Rightarrow W \Rightarrow e\nu)$
- For A_L^W want to increase purity of signal wrt background (which would otherwise dilute asymmetry)
- Spin-independence of cuts important,
  determining absolute efficiency of cut to high precision is not
- Use an isolation cut since physics predicts e candidates from W are isolated :
  - Require (sum of EMCal energy for neutral particle) $+$ (sum of momentum) overlapping cone about e candidate of 0.5 rads $<$ 2 GeV
  - (minimum $E > 0.15$ GeV, $0.2 < p_T < 15$ GeV/c, latter reduces fake tracks)
  - Cut on DC tracks $|\alpha| <$ 1 mrad to reduce charge mis-identification
- Net effect is to keep $> 70\%$ of signal, reduce background approximately factor of 5

Effects of Isolation Cuts : Negative Charge



- Black points = before isolation cut
- Red points = after isolation cut
- Background reduced by factor of 5

Effects of Isolation Cuts : Positive Charge



- Black points = before isolation cut, Red points = after isolation cut
- Net effect is to keep $> 70\%$ of signal, reduce background by $\times 5$
- For asymmetry analysis, define Background Region (12-20 GeV/c)
- For asymmetry analysis, define Signal Region (30-50 GeV/c)

Extracting the Parity-Violating Single Spin Asymmetry A_L^W

- Denoting positive beam helicity by $+$ and negative by $-$, A_L^W is defined :

$$A_L^W \equiv \frac{\sigma(\overrightarrow{p}p \Rightarrow W) - \sigma(\overleftarrow{p}p \Rightarrow W)}{\sigma(\overrightarrow{p}p \Rightarrow W) + \sigma(\overleftarrow{p}p \Rightarrow W)}$$

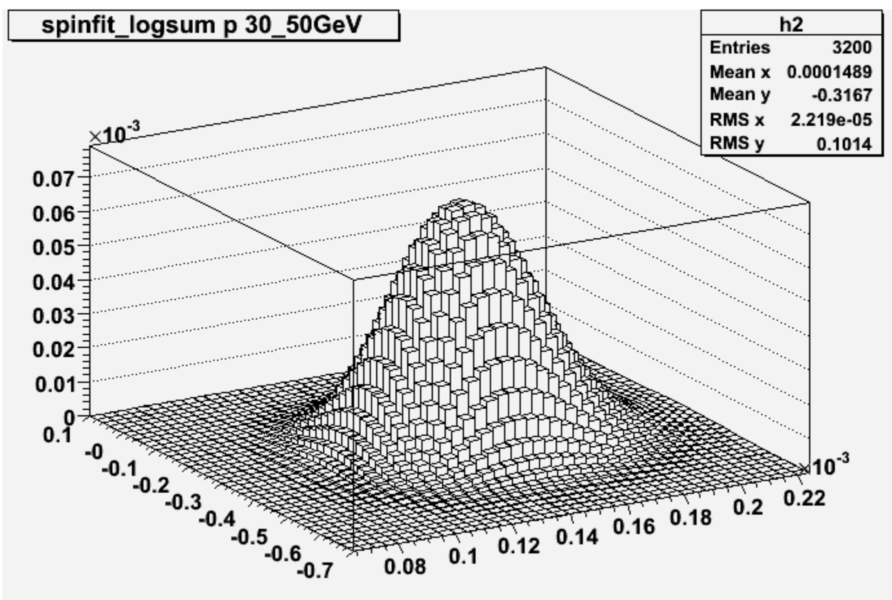
$$\approx \frac{1}{P}\frac{N^+(e)/\mathcal{L}^+ - N^-(e)/\mathcal{L}^-}{N^+(e)/\mathcal{L}^+ + N^-(e)/\mathcal{L}^-}$$

- Here N is the electron yield, $\mathcal{L}$ is integrated luminosity, P is luminosity-weighted polarization
- Get one measurement treating "blue" beam as polarized, averaging over "yellow" beam
- Get second measurement treating yellow beam as polarized, averaging over blue beam
- Ideally we'd do this as function of $\eta(e)$ but statistics are too limited
- Going from $\eta(e)$ to $\eta(W)$ from central arm measurements best done in global fit
- Asymmetry extracted using all helicity combinations with maximum-likelihood method

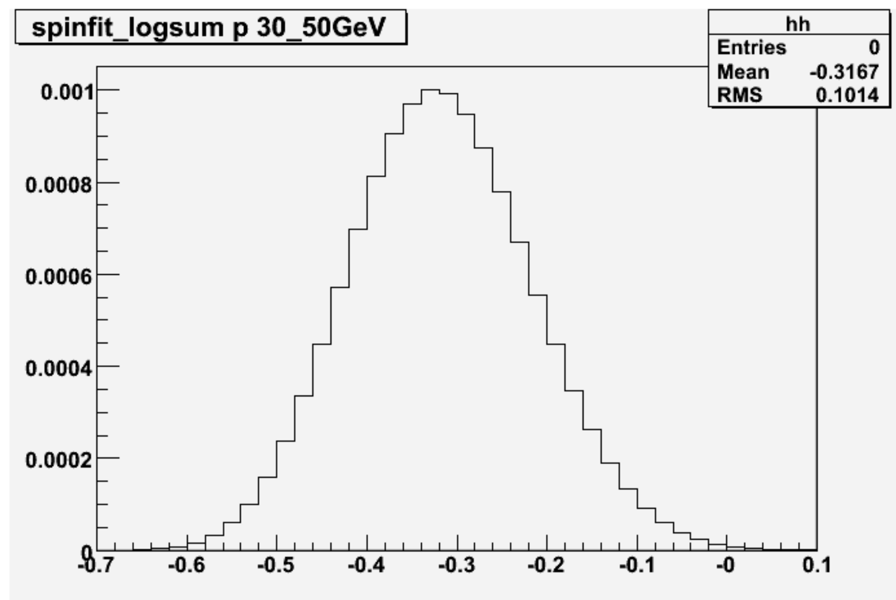
- Can extract asymmetry using all helicity combinations with maximum-likelihood method
- Denoting beam polarization by P, raw asymmetry by ϵ so $\epsilon = AP$:

$$\begin{aligned}
\sigma^{++} &\approx (1 + AP_B)(1 + AP_Y)\sigma \\
\sigma^{+-} &\approx (1 + AP_B)(1 - AP_Y)\sigma \\
\sigma^{-+} &\approx (1 - AP_B)(1 + AP_Y)\sigma \\
\sigma^{--} &\approx (1 - AP_B)(1 - AP_Y)\sigma
\end{aligned}$$

- Use likelihood function to find best value of raw asymmetry ϵ



Likelihood scan of (ϵ, σ) for $30 < p_T < 50$ GeV for e^+

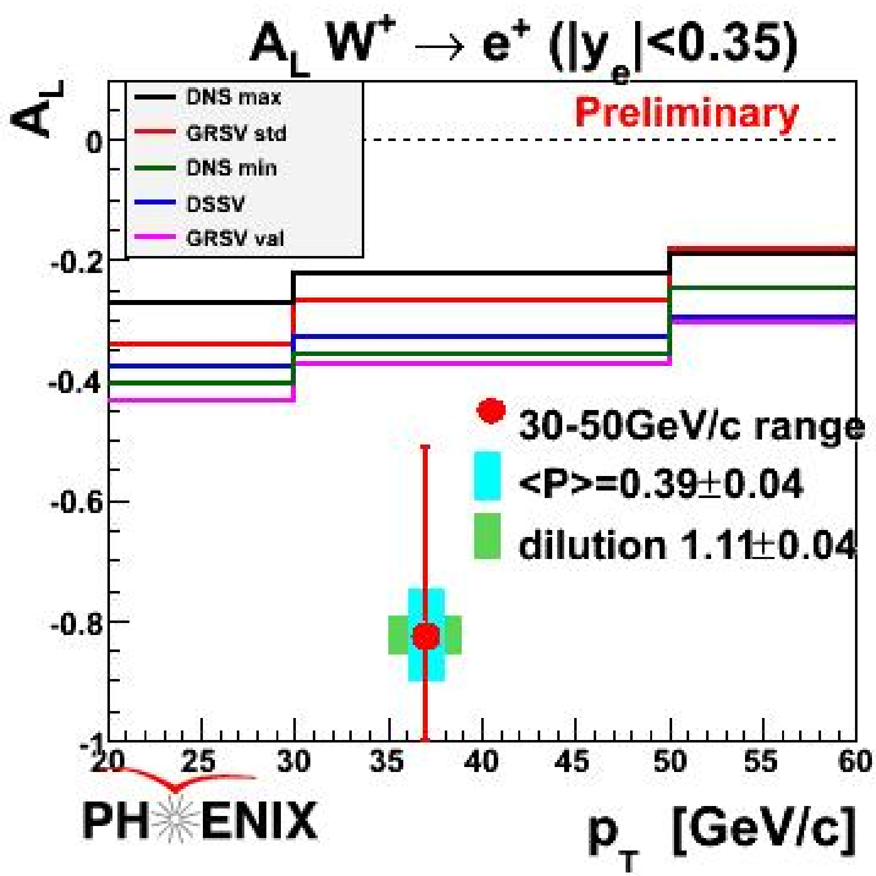


Projection of (ϵ, σ) onto ϵ axis for $30 < p_T < 50$ GeV for e^+

Parity-Violating Single Spin Asymmetry $A_L(\vec{p}p \to W^+ \to e^+)$

- Preliminary result, using $P_B = 0.38 \pm 0.04$ and $P_Y = 0.40 \pm 0.04$ $(\delta P/P = 9.2\%)$
- Raw asymmetry in background region (12-20 GeV/c) consistent with 0 : $\epsilon_{\rm raw}^{\rm Bkgd} = 0.035 \pm 0.047$
- Raw asymmetry in signal region (30-50 GeV/c) inconsistent with 0 : $\epsilon_{\rm raw}^{\rm Signal} = -0.29 \pm 0.11$
- $A_L = \frac{1}{P} \times \epsilon_{\rm raw} \times D$, correct for dilution of A_L by Z and QCD background $(D = 1.11 \pm 0.04)$

$$\boxed{A_L(\vec{p}p \to W^+ \to e^+) = -0.83 \pm 0.31}$$

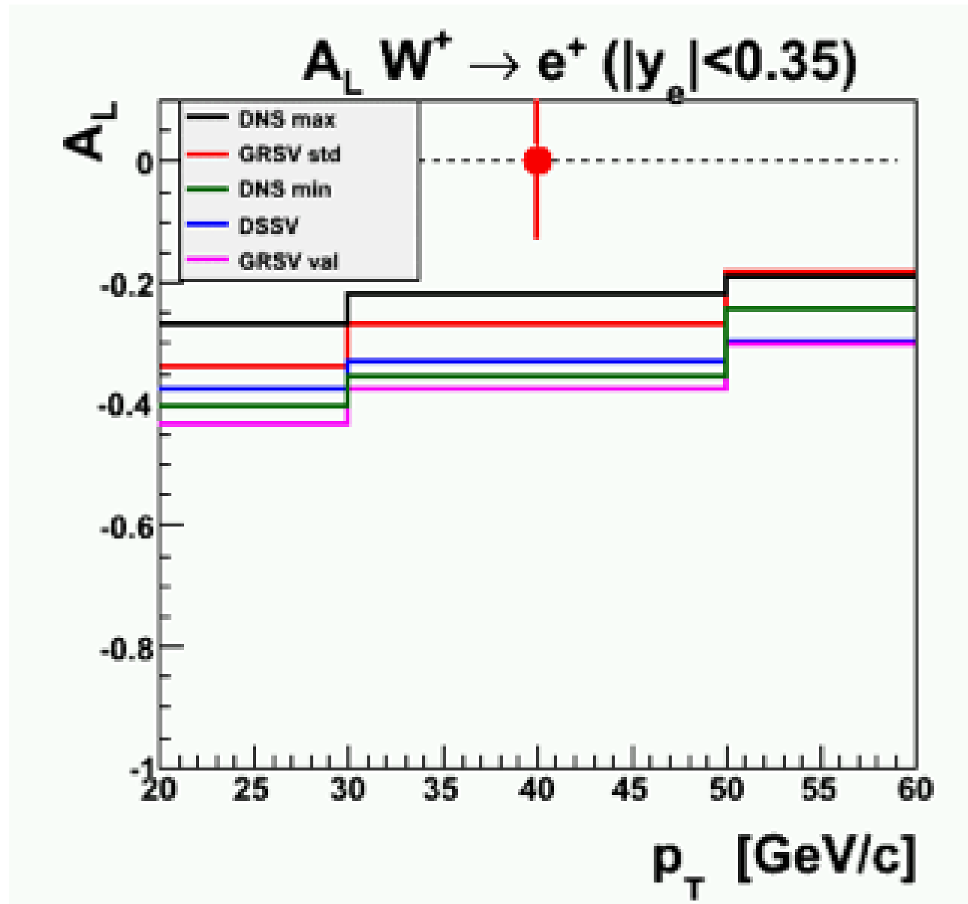


Near Term Future : $\sqrt{s} = 500$ GeV pp Run in 2011

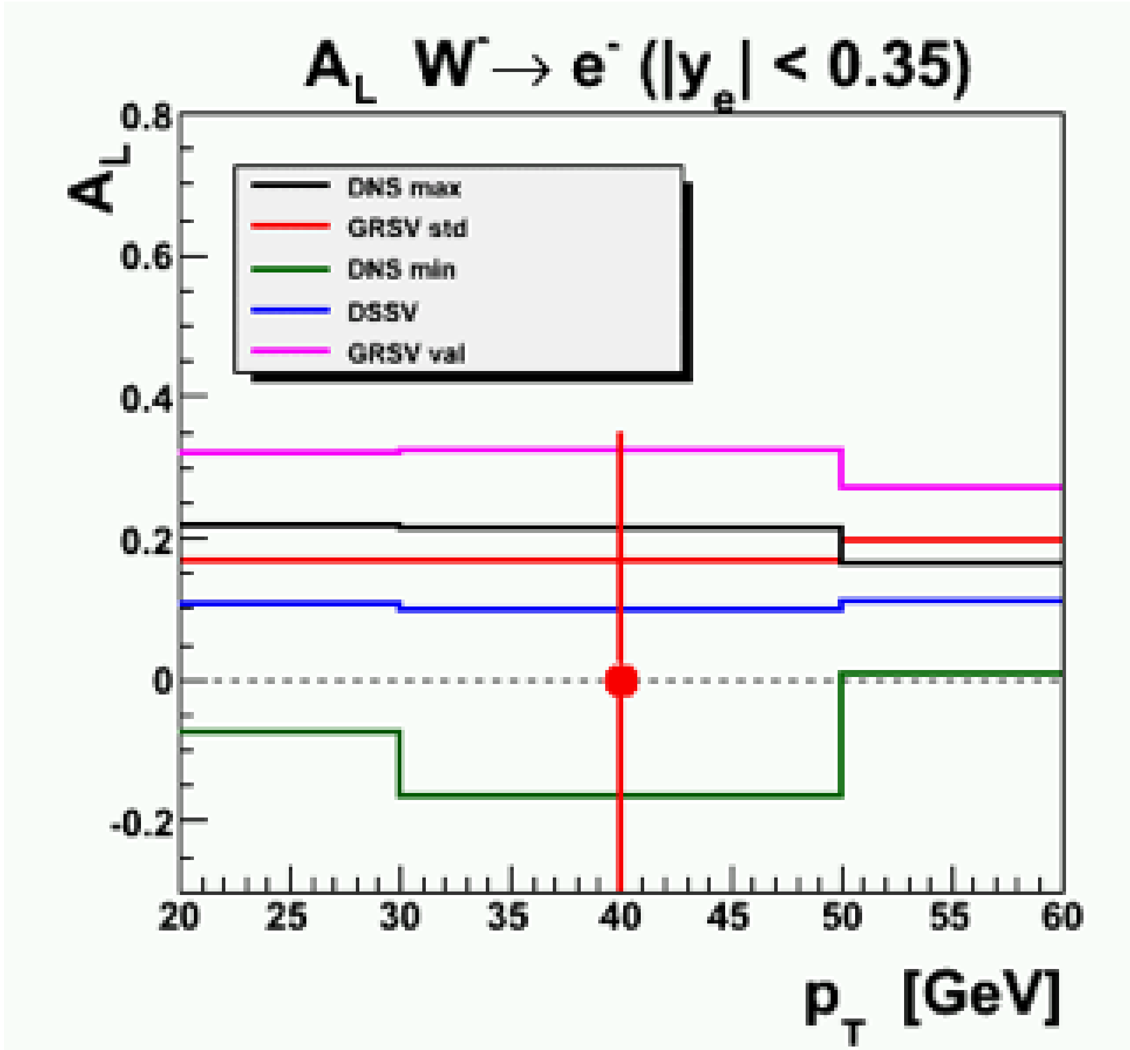
- Expectation is for $\int \mathcal{L} dt = 50$ pb^{-1} (no vertex cut, ≈ 25 pb^{-1} after cut), $P = 50\%$
- Major upgrade of muon arms for $pp \to W \to \mu + \nu_\mu$ in forward region (See Yoshi Fukao's talk tomorrow)
- Some changes to central arm during shutdown : HBD removed, Si VTX installed (!), maintenance on DC and PC

- Increased rate of conversions expected, ≈ 3 (but can eliminate many with cuts)
- Acceptance partially reduced for $|z| > 20$ cm by VTX components
- Expect improvements in efficiency of isolation cut
- DC and PC maintenance should lead to increased detector active area

$\Rightarrow$ Factor 2 reduction in δA_L over Run 9



Near Term Future : $\sqrt{s} = 500$ GeV pp Run in 2011



- $A_L(\vec{p}p \rightarrow W^- \rightarrow e^-)$ challenging measurement
- Will require 300+ pb^{-1} and 70% polarization if we can get it, and optimal detector performance

Summary and Outlook

- Developed analysis techniques to isolate $W \rightarrow e$ signal above backgrounds
- Clear evidence for $W^{\pm} \rightarrow e^{\pm}$ at $|\eta| < 0.35$ in PHENIX central arms
- Preliminary determination of single-spin parity-violating asymmetry :
  $A_L^W(\vec{p}p \rightarrow W^+ \rightarrow e^+) \;=\; -0.83 \;\pm\; 0.31$
- Analysis underway for cross-section estimates, final $A_L^{W^{\pm}}$ determinations

- Upgrades will help refine analysis, add acceptance and new physics channels :
  - Si Barrel vertex detectors in PHENIX central arms
  - Muon arms : RPCs + muon trigger upgrade : $W \rightarrow \mu$ signal $1.2 < |\eta_\mu| < 2.2$

- C-AD getting closer to design luminosity at $\sqrt{500}$ GeV, $\approx 40\%$ polarization
- Will need 300+ pb^{-1} integrated luminosity, 60% polarization to meet goals of program